Design optimization of 600 A–13 kA current leads for the Large Hadron Collider project at CERN

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Abstract
The requirements of the Large Hadron Collider project at CERN for high-temperature superconducting (HTS) current leads have been widely publicized. CERN require hybrid current leads of resistive and HTS materials with current ratings of 600 A, 6 kA and 13 kA. BICC General Superconductors, in collaboration with the University of Southampton, have developed and manufactured prototype current leads for the Large Hadron Collider project. The resistive section consists of a phosphorus de-oxidized copper conductor and heat exchanger and the HTS section is constructed from BICC General's (Pb, Bi)2223 tapes with a reduced thermal conductivity Ag alloy sheath. We present the results of the materials optimization studies for the resistive and the HTS sections. Some results of the acceptance tests at CERN will be discussed.

1. Introduction

The Large Hadron Collider, LHC, due to be switched on in 2005, will produce collisions of protons at an energy of 7 TeV [1]. To achieve the required accelerating speeds to produce such collisions, the LHC will be equipped with approximately 8000 superconducting magnets [1] requiring 3.6 MA of current [2]. By using hybrid high-temperature superconducting (HTS) current leads, CERN can make a substantial saving on the cryogenic load of the LHC machine [1].

After extensive studies into the conceptual design of the current leads CERN have opted to use a mode of cooling utilizing available gaseous helium at 20 K from the return lines of the beam screen cooling lines in the LHC [2–4].

BICC General was selected by CERN in 1997 to take part in a market survey relating to the design, manufacture and supply of HTS current leads for the LHC project. To date BICC General has supplied a prototype pair of 13 kA and a prototype assembly of four 600 A current leads to CERN. In this paper we present some of the work undertaken to select and optimize suitable materials to be used in the design and manufacture of the prototype leads.

2. Specifications

Table 1 shows some of the main specifications of the HTS hybrid prototype current leads already tested by CERN. Also shown is the specification for the HTS current leads required by the Lawrence Berkeley National Laboratory for cryogenic feed boxes to be supplied to the LHC project under the US-LHC project funded by the US DOE.

3. Choice of materials

The HTS assemblies used in the hybrid current leads were manufactured from BICC General's, specifically designed, Cryobicc$^{\mathrm{TM}}$ (Pb, Bi)2223 tapes. The choice of the sheath material of the 2223 tapes was clearly an important parameter in the success of the prototypes. The sheath material has a direct influence on the magnitude of the heat leak to the liquid helium (LIH) bath and also a significant influence on

Table 1. Current lead specifications.

General specification	CERN 600 A	CERN 13 kA	LBNL 7.5 kA
Rated current	600	13 000	7500
No of units/prototype	4	2	2
Overall length (mm)	1200	1500	1450
Q (in standby mode) (W)	<0.07	<1	<0.4
Mass flow (He gas at 20 K) (g s^{-1})	<0.04	<1	<0.45
Q (at rated current) (W)	<0.08	<1.5	<0.7
Current ramping (A s^{-1})	5000	250	100
R(contact), 4 K (Ω)	$<3 \times 10^{-8}$	$<2 \times 10^{-9}$	$<5 \times 10^{-9}$
R(contact), 50 K (Ω)	$<1 \times 10^{-6}$	$<2 \times 10^{-8}$	
Electrical insulation against ground (kV)	1.1	3.5	1.5
Leakage current at insulation voltage (μA)	<1	<3.5	<50
Design pressure (bar)	5.25	5.25	4.4
ΔP at rated current (mbar)	<50	<50	<50
Thermal stability time constant current decay (s)	5	120	10
Max T of HTS to remain superconducting at rated current (K)	60	60	60

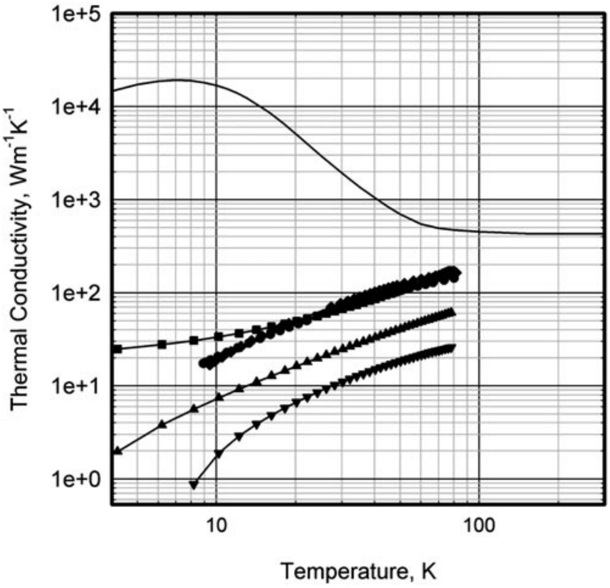

Figure 1. Temperature dependence of thermal conductivity of sheath materials suitable for use in HTS current leads. ——, Ag 9999 [8]; ■, AgAu4%; ◆, AgAu45Mg0.25%; ●, AgAu4% Mn0.25%; ▲, AgAu10%; ▼, AgAu15%.

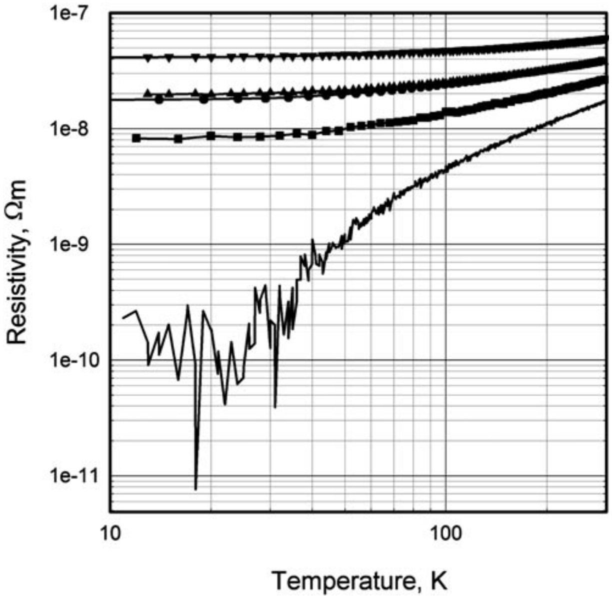

Figure 2. Temperature dependence of electrical resistivity of sheath materials suitable for use in HTS current leads. ——, Ag 9999; ■, AgAu4%; ◆, AgAu45Mg0.25%; ●, AgAu4% Mn0.25%; ▲, AgAu10%; ▼, AgAu15%.

the survival properties of the prototypes during the simulated fault conditions.

Figure 1 shows the thermal conductivity as a function of temperature for various sheath materials currently being used to manufacture HTS devices. These data agree with previous reports [5] that an increase in the amount of Au in the Ag matrix material reduces the thermal conductivity. Theoretically the relationship between thermal conductivity and the amount of Au is inversely related to the electrical resistivity by the Wiedemann–Franz law [6]. The temperature dependence of the electrical resistivity of various sheath materials used in the manufacture of 2223 tapes is shown in figure 2. As predicted the temperature-dependent resistivity of the Ag alloy materials increases with the increased addition of Au found in the alloy materials. The results of resistivity and thermal conductivity are in close agreement with the Wiedemann–Franz law. From the sets of results seen in figures 1 and 2 it is clear that the number of tapes used in the HTS assembly may not simply be dictated by the minimum achievable heat leak but has to be balanced with its ability to survive the simulated fault conditions. Furthermore, an additional shunt may be required to satisfy the survival conditions by carrying the decaying current at elevated temperatures. The choice of material for the resistive heat exchanger is also not only dictated by the effort to reduce the heat leak introduced down the current lead by the transmission of the current but attention needs to be paid to the stability of the material, particularly under fault conditions [5]. Figure 3 shows the temperature dependence of the resistivity for various grades of Cu materials. The resistive conductors used in the hybrid current leads were manufactured from phosphorus deoxidized Cu, which has been shown to be more stable than the less resistive oxygen-free, high-conductivity copper (OFHC). However, interface regions of HTS elements were manufactured from OFHC. In order to carry out the initial design study

Table 2. Magnitudes of measured contact resistivities.

	Contact resistivity (Ω cm^{-2})	
Configuration	$T = 77$ K	$T = 4$ K
HTS/HTS	7.2×10^{-8}	2.4×10^{-8}
HTS/Cu	3.6×10^{-7}	1.6×10^{-9}
Cu/Cu	3.7×10^{-7}	—

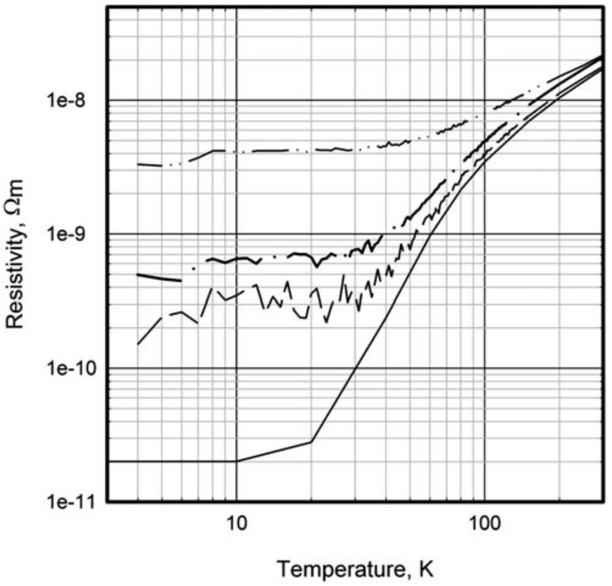

Figure 3. Temperature dependence of electrical resistivity of Cu materials suitable for use in HTS current leads. ——, Cu 9999 [9]; – – –, high conductivity Cu(1); — · —, high conductivity Cu(2); — · · —, phosphorus de-oxidized Cu.

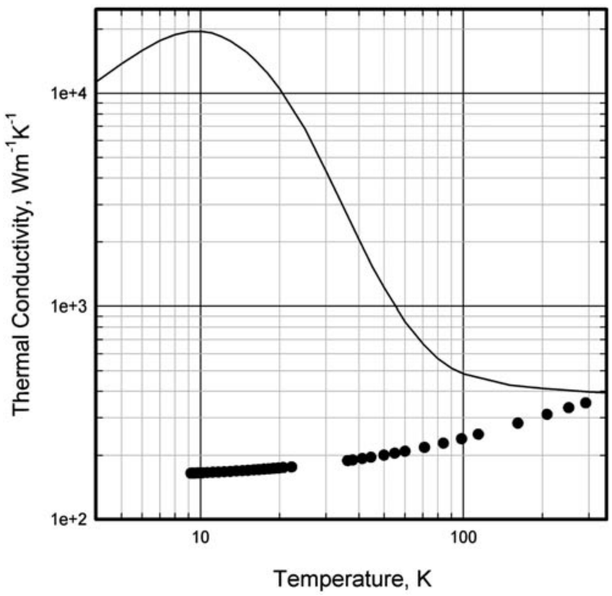

Figure 4. Temperature dependence of thermal conductivity of Cu used for the resistive section of the CERN prototype current leads. ——, Cu 9999 [8]; ●, phosphorus de-oxidized Cu.

on the properties of the leads, the thermal conductivity of the phosphorus de-oxidized copper was measured as a function of temperature, figure 4.

The electromechanical joints between the resistive section and HTS assemblies and the HTS assemblies and LTS conductors are also important areas that have required materials optimization. In order to avoid excess Ohmic heating which would increase the heat generation during operation, low contact resistances are required at Cu to Cu, Cu to HTS and Cu to LTS interfaces. Figure 5 shows the temperature dependence of electrical resistivity of some common low-temperature solder materials. It is clear from the figure that some of these materials are themselves superconducting in the temperature range of 4–10 K. As well as the low resistivity of the solder materials, it is also important to consider the mechanical properties of the materials. It is desirable to utilize solders with a range of melting temperatures. Furthermore, it is important to know the temperature range from onset to the point the solder is fully molten. Figure 6 shows the thermomechanical analysis as a function of temperature of various common solders. It can be seen that some solders have a broad melting transition and become ‘softer’ at temperatures much lower than their ‘melting temperatures’. When choosing suitable solders it is important to consider the range of melting temperatures and also the mechanical properties of the solders prior to and during the melting region.

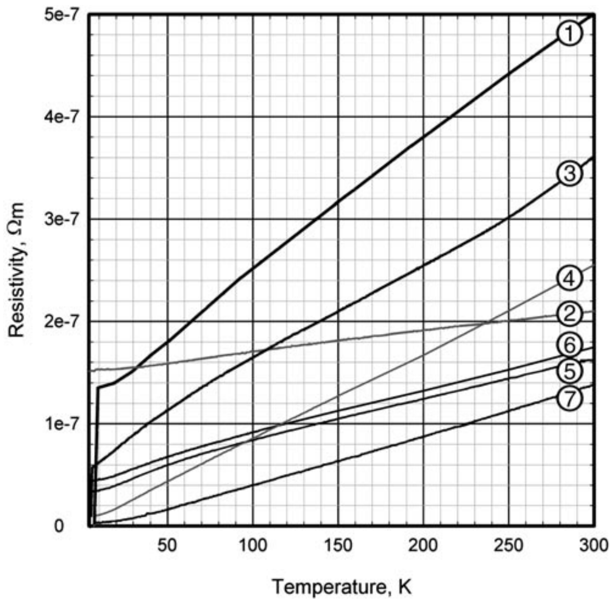

Figure 5. Temperature dependence of electrical resistivity of solder materials suitable for use in HTS current leads.
1, Bi(50)Pb(20)Sn(30); 2, Ag solder; 3, In(56)Bi(44);
4, Pb(94)Sn(5)Ag(1); 5, In(80)Pb(15)Ag(5); 6, In(62)Pb(36)Ag(2);
7, Sn(60)Pb(40).

Prior to the design study for the prototype current leads, further optimization of the solder materials was undertaken by measuring the contact resistance of typical solders at 77 K and 4 K. Table 2 shows the magnitude of the measured resistivities of Bi(50)Pb(20)Sn(30) solder shown in figure 5. The contact resistivities were measured for the various configurations involved in the HTS hybrid current leads.

Table 3. Prototype current lead test results.

	CERN 13 kA			
	Design		Measured	
Design parameter/specification	$I = 0$	$I = 13$ kA	$I = 0$	$I = 13$ kA
Temperature at warm end of HTS (K)	40	40	40	40
Temperature safety margin, stable at 60 K	60	60	60	60
Mass flow of 20 K gas flow (1.3 bar) to maintain HTS at operating T (g s^{-1})		1	<0.49	0.75
ΔP (mbar)	<50	<50	<3	<3
Heat leak to LIH bath (W)	0.71	0.99	0.8	<1
Thermal runaway stability. HTS to remain superconducting after temporary loss of coolant	—	✓	—	✓
HTS elements not damaged after quench triggered by voltage across HTS. Trigger voltage (mV)	—	>10	—	200

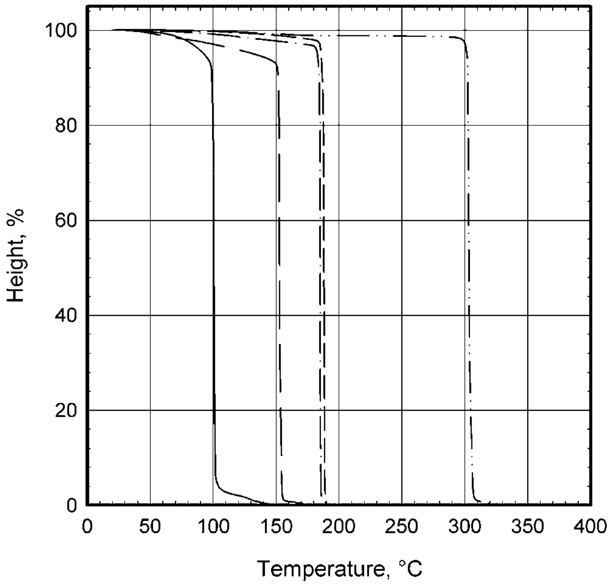

Figure 6. Thermomechanical analysis of solder materials suitable for use in HTS current leads. ——, Bi(50)Pb(20)Sn(30); – – –, In(80)Pb(15)Ag(5); — · —, Sn(60)Pb(40); – – –, Sn(62)Pb(36)Ag(2); — · · —, Pb(94)Sn(5)Ag(1).

4. Lead results

Figure 7 shows the prototype 13 kA and the prototype assembly of four 600 A current leads supplied to CERN. Both prototypes passed the comprehensive tests at CERN without any repairs or alterations. Table 3 shows the results of the CERN tests carried out on the prototype 13 kA current leads. The table shows the prototype was successful.

The results for the 'survival' characteristics of the 13 kA are particularly interesting as the current lead significantly exceeded the initial specification of a 10 mV trigger voltage prior to reducing the current level to standby. This is of particular importance from a protection standpoint, as the tunnel environment that the leads will operate in is known to be relatively noisy [7]. Further details of the CERN qualification tests for the prototype assembly of four 600 A leads will be published by CERN in the near future.

Figure 7. Prototype 13 kA current lead, with prototype assembly of four 600 A current leads (inset).

5. Conclusions

In this paper we have reviewed some of the major parameters that require optimizing prior to current lead design. It is clear that to achieve an optimum design concept it is necessary to optimize the electrical and thermal properties of the HTS tapes to be used in the current lead. Of equal importance is the optimization of the Cu materials to minimize the heat leak to the LIH bath and maximize the stability of the resistive section.

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